

Large-Scale Structure at High Redshift

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Abstract. I discuss and illustrate the development of large-scale structure in the Universe, emphasising in particular the physical processes and cosmological parameters that most influence the observationally accessible aspects of structure at large redshift. Statistical properties of this structure can be measured from the apparent positions of faint galaxies and quasars; the structure can be mapped in three dimensions by obtaining redshifts for large samples of such objects; it can be studied using foreground absorption in the spectra of quasars; finally the mass distribution can be constrained by measuring the gravitationally induced distortion of background galaxy images. The first and last of these techniques require deep imaging of large areas of the sky with the best possible image quality. The second and third will require 8m-class telescopes with efficient multiobject spectrographs. For QSO absorption line spectroscopy high spectral resolution is also important.

1 Introduction

The term “large-scale structure” normally refers to the distribution of matter on scales larger than those of individual galaxies or galaxy clusters. On these scales objects have not yet had time to collapse fully and to come to equilibrium, and so their observed morphology is determined principally by the properties of the initial fluctuations from which they grew, and by the physical processes which amplified those fluctuations. As a result, there is hope that by studying large-scale structure we may learn directly about the mechanisms which imprinted irregularities on our otherwise almost homogeneous Universe.

Recent observational work on large-scale structure has focussed primarily on galaxy redshift surveys, the most recent example, and also the largest so far, being the Las Campanas Redshift Survey of more than 25,000 galaxies (Schechter et al 1996). The planned 2dF and Sloan surveys will increase this already impressive number by more than an order of magnitude. Surveys of this kind can be analysed in many ways but two broad approaches can be distinguished, quantitative analysis of low-order statistics and determinations of the morphology and topology of structure through detailed maps. The first approach typically aims to discriminate between specific models such as the many variants of the cold dark matter (CDM) model, while the second is more empirical and might, for example, provide a test for the broad class of theories which assume that structure grew through gravitational amplification of an initially gaussian density fluctuation field. In the nearby Universe independent distances to galaxies can be

measured sufficiently well for studies of peculiar velocities and large-scale flows to provide powerful additional constraints on the large-scale mass distribution.

Theoretical discussions of large-scale structure vary from the development of purely descriptive statistics for the present distribution of galaxies (e.g. power spectra, position and velocity correlations of all orders, counts-in-cells, void probabilities and the relations between these quantities) through dynamical treatments of structure growth based on perturbation theory, to massive attempts to simulate the development of structure from the linear into the fully nonlinear regime. In this contribution I will focus mainly on the latter since simulations produce results that are easy to appreciate visually and can be compared directly with observational data. The descriptive statistics do, of course, provide the main quantitative comparison between simulation and observation, while the perturbation theory gives a powerful means for checking that the numerical simulations are, in fact, correct. The main difficulty when comparing theory and observation is that most current simulations predict the distribution of dark matter whereas almost all the observational data refer to the distributions of gas or of galaxies. The first attempts to simulate both gas dynamics and galaxy formation have now been carried out, but much of the physics cannot be treated properly and the results must be regarded as very uncertain.

In the next section I discuss simulations of structure formation in somewhat more detail in order to show how the evolution of large-scale structure depends on the cosmological model in which it is occurring. I then summarise our current understanding of the relation between visible structure and that in the mass in order to indicate how the predictions of N-body simulations may be related to observation. Section 4 discusses the techniques available for measuring large-scale structure at high redshift and assesses what may be achievable with the next generation of telescopes if current ideas about structure formation are correct.

2 Evolution of Structure in the Dark Matter

Standard structure formation theories suppose the dark matter to be pregalactic, collisionless, and gravitationally dominant. The only significant agent affecting the recent development of its spatial structure is then gravity, and on large scales the distribution of the visible material is also structured primarily by the gravity of the dark matter. The currently most popular, and certainly the most thoroughly investigated structure formation models suppose that the dark matter is non-baryonic and that the initial deviations from uniformity were produced by quantum fluctuations during an early inflationary period. The latter assumption implies that density fluctuations at early times are a gaussian random field and so are fully specified by their power spectrum alone. The form of this power spectrum depends on the details of the inflation model and on the nature of the dark matter. Since early work showed that hot dark matter, specifically neutrinos with a mass of a few tens of eV, cannot produce the kind of large-scale structure we see (they produce structure too late and on scales which are too

large) inflationary models now all assume the dominant matter constituent to be some form of cold dark matter (CDM). Topological relics of an early phase transition are another possibility for imposing structure on an otherwise uniform universe (e.g. Brandenberger 1994); I will not discuss them further here.

Within the general family of CDM models, several cures have been proposed for the inability of the original “standard” CDM model simultaneously to fit data on large-scale structure and the fluctuation amplitude measured by COBE. All involve adding an additional complexity to the model. Thus “tilted” CDM (or TCDM) supposes that a non-standard inflation model produces fluctuations with a slightly different scaling of amplitude with wavelength; hot plus cold, or mixed dark matter models (H+CDM or MDM) suppose that a small fraction of the dark matter is in the form of stable massive neutrinos; τ CDM supposes that the decay of an unstable massive neutrino at early times has left a relativistic neutrino background of higher density than in the standard model; Λ CDM supposes that a cosmological constant makes a significant contribution to the present energy density; open CDM (OCDM) supposes the curvature radius of the Universe to be comparable to its observable extent, rather than much larger as predicted by standard inflation. With a suitable choice of the additional free parameter each of these models can be made to give a rough fit both to the COBE amplitude and to observed large-scale structure.

To break the degeneracy between these models, one must appeal to other data. Large-scale flows may exclude low density models (Dekel 1995); combining measures of the Hubble constant and of globular cluster ages may exclude high density models (Freedman et al 1994); in a high density universe the observed baryon fraction in galaxy clusters may be inconsistent with big bang nucleosynthesis (White et al. 1993); the Hubble diagram for distant SNIa or the frequency of gravitational lensing of quasars may rule out models with a substantial cosmological constant (Perlmutter et al 1996; Kochanek 1995). For the purposes of this talk, however, the major difference between the high and low density models lies in the predicted evolution of large-scale structure with redshift.

This difference is illustrated in figures 1 to 3. These plots show thin slices through some large N-body simulations of a “standard” CDM model (SCDM) and of some variants that are generally thought to be consistent both with COBE and with present-day large-scale structure. These pictures were made by Joerg Colberg from simulations carried out on the Garching T3D parallel supercomputer as part of the programme of the Virgo Consortium (Jenkins et al, in preparation). The simulations used 17 million particles to follow the evolution of the matter distribution within comoving cubic regions of present size $240h^{-1}\text{Mpc}$; they are able to resolve structures down to a linear scale of $25h^{-1}\text{kpc}$ and a mass scale corresponding to the halo of a Milky Way-like galaxy. The thickness of each slice is about 10% of its width. The dark matter distribution is smoothed adaptively to give an overdensity which is represented on the same logarithmic colour scale in all plots. Objects containing fewer than 20 particles are not visible.

Structure is much more prominent at $z = 0$ in the low density models (OCDM

and Λ CDM) than in the Einstein-de Sitter models (τ CDM and SCDM). This is a reflection of the well-known “bias” needed to make high density models consistent with the observed galaxy distribution. Although all four models have about the same abundance of massive quasi-equilibrium objects – rich galaxy clusters – models with a high total matter content achieve this with relatively low fluctuation amplitudes, lower, in fact, than those measured for the galaxy distribution. For low density models the required amplitude is a better match to the observed strength of galaxy correlations on large scales. Biasing must therefore enhance the contrast of structure in the galaxy distribution for the τ CDM and SCDM models (see, for example, fig. 16 of Davis et al 1985) whereas for the other models it is not required. Fig. 1 suggests, independent of this, that more fine-scale structure is to be expected in high density models. The difference between the two high density models gives a visual impression of the “lack of large-scale power” which has often been cited as ruling out standard CDM; large-scale correlations are consistent with those measured for galaxies and galaxy clusters in the τ CDM model, but are too weak in SCDM.

The differences in evolution between the various models are quite striking at higher redshift. By a redshift of three the $\Omega = 1$ models look much more uniform, the Λ CDM model has changed rather little, and the OCDM model has hardly changed at all. These differences reflect, of course, the different behaviours of the linear growth factor. In the open case growth effectively “switches off” at $1+z \sim \Omega_0^{-1} \sim 5$. In the Λ CDM case this switch-off occurs at $1+z \sim \Omega_0^{-1/3} \sim 1.5$, while for an Einstein-de Sitter universe growth continues until $z = 0$. Thus in low density models we expect much more large-scale structure in the high redshift mass distribution than if $\Omega = 1$. Because of the bias galaxy clustering is expected to evolve less rapidly, but, as I discuss next, the galaxies themselves evolve more rapidly in this case. It is interesting to note that the pattern of the final large-scale structure is still visible at $z = 3$ in the high density models and would be more prominent in the biased but observable galaxy distribution.

3 Bias and its evolution with redshift

Except in the few situations where its gravitational lensing effects can be measured directly, the large-scale structure seen in figs 1 – 3 must be investigated using “tracers” like galaxies, galaxy clusters, quasars, or the gas seen as quasar absorption lines. The simplest method is to map out the spatial distribution of the tracer, to characterise its properties by some appropriate statistics, and then to use a model to relate the statistics to those of the dark matter. Although direct measurements of peculiar velocities for nearby objects are good enough to map the local mass distribution (Dekel 1995; Strauss and Willick 1996), this is impossible at higher redshift (except that peculiar velocities for galaxy clusters may be measurable using the kinematic Sunyaev-Zel’dovich effect, e.g. Haehnelt and Tegmark 1996). Peculiar velocities can be measured statistically at high redshift through the anisotropies they induce in the apparent spatial clustering

of galaxies. Here, however, as with all clustering statistics, the interpretation hinges critically on the relation between the tracer and the mass distributions, in other words on the “bias”.

In hierarchical clustering theories a good model for the bias of galaxy clusters can be derived from the gaussian initial conditions (Kaiser 1984). The current amplitude of superclustering depends on cluster abundance and on the shape and amplitude of the linear power spectrum of mass fluctuations; it has no direct dependence on Ω and Λ (Mo et al 1996). The evolution of superclustering *does* depend strongly on the cosmological parameters because they change the history of the linear growth factor and so the amplitude of linear fluctuations at high z . To apply this test to a sample of distant clusters one would need to know only: (a) the abundance of the sample; (b) that it is effectively complete for all clusters more massive than some (possibly unknown) threshold; and (c) the amplitude of cluster-cluster correlations.

For more abundant tracers like galaxies or absorbing gas, much more physics must be included to get a realistic model for bias. In hierarchical theories residual gas is supposed to collapse dissipatively within the halos provided by the dark matter, settling to form centrifugally supported star-forming disks at their centres (White and Rees 1978; Fall and Efstathiou 1980). Recent work has shown that such a model, supplemented by Toomre’s (1976) idea that ellipticals and bulges form by the merging of early stellar disks, can account qualitatively (and often quantitatively) for most of the systematics of the observed galaxy population; e.g. the present distributions of luminosity, colour, and morphology, and their correlation with environment (Kauffmann et al 1993), the counts, redshift distributions and morphologies of distant galaxies (Cole et al 1994; Kauffmann et al 1994; Heyl et al 1995; Baugh et al 1996a), the observed evolution of the population in rich clusters (Kauffmann 1995, 1996a; Baugh et al 1996b), and the star formation history of disk galaxies as inferred from nearby spirals and from the damped Ly α absorbers in quasar spectra (Kauffmann 1996b). This “semi-analytic” approach uses simplified but physically based models to treat each of the important processes (cooling, star formation, feedback of energy and of metals, evolution of the stellar populations, rates for galaxy merging). Its results can be compared with a much broader range of data than any feasible simulation. The main current difficulty, visible in most of the papers cited above, is a substantial overprediction of the number of faint galaxies in the local Universe. Much of the assembly and star-formation of galaxies is predicted to take place late (at or below $z \sim 1$) if $\Omega = 1$, suggesting rapid evolution of the tracers of large-scale structure; earlier formation is possible in low density universes.

Direct simulations which include a dissipative gas component have confirmed (or inspired) several aspects of the above work, showing that gas does cool off to make centrifugally supported disks at the centres of dark matter halos, and that these can plausibly be identified as the progenitors of galaxies and galaxy clusters (Cen and Ostriker 1992; Katz et al 1992; Evrard et al 1994). It is currently impossible to simulate the formation of individual galaxies in regions large enough to study large-scale structure, and the differing compromises with numer-

ical limitations made by different groups show up as substantial discrepancies in their predictions for galaxy masses and sizes, for the fraction of gas turned into galaxies, etc. Although the results of these simulations are encouraging, none of their quantitative predictions for “galaxy” clustering can yet be considered reliable. The situation may be better in the case of quasar absorbers. Simulations which include both the dark matter and a dissipative gas component subject to a photoionising UV background seem to give considerable insight into the nature of the absorbers and into their spatial distribution. It appears relatively easy to explain both the observed abundance as a function of HI column density and the observed coincidence rate between neighboring lines-of-sight (Cen et al 1994; Hernquist et al 1996; Katz et al 1996). It is nevertheless still too soon to conclude that the simulations have converged to the physically correct answer.

The most promising approach to understanding galaxy bias and its evolution may be a combination of the semi-analytic galaxy formation models either with similar semi-analytic models for clustering (e.g. Mo and White 1996) or with N-body simulations which do not explicitly follow the gas. A first attempt at each of these routes was made by Kauffmann et al (1996). This paper shows how the bias in the present galaxy distribution can be calculated as a function of galaxy luminosity, colour, or morphological type, as well as how the consequences of bias for any particular statistic can be evaluated using N-body simulations. Extensions of this work to larger simulations such as those shown in figs 1 – 3 should allow much more detailed predictions for the evolution of large-scale structure in the galaxy distribution. These can then be compared directly with the kinds of data reviewed in the next section.

4 Measuring large-scale structure at high redshift

4.1 Angular correlations

As shown most recently by the Hubble Deep Field, at faint magnitude limits the sky is covered with galaxies. With ground-based telescopes it is possible to get magnitudes, positions and colours for objects as faint as $B \sim 27$ whereas spectroscopy, even on 10m telescopes is limited to $B \sim 24$. The faintest galaxies seen are plausibly (although not necessarily!) the most distant, although the colours of those found in the HDF suggest, somewhat surprisingly, that only a few percent are at redshifts beyond 2.5 (Madau et al 1996; Lanzetta et al 1996; Steidel et al 1996). This appears to require most of the star formation and assembly of present-day galaxies to take place *after* $z = 2.5$. For these faint samples almost the only available clustering information is the angular two-point correlation function. This may be written as:

$$w(\theta) = A_\gamma \int_0^\infty dz \left(\frac{1}{N} \frac{dN}{dz} \right)^2 \xi(\theta d_A, z) \frac{H(z) d_A(z) (1+z)}{c} \quad (1)$$

where A_γ is a numerical constant which depends weakly on the slope of the correlation function, $N(z)$ is the number of objects per unit redshift, $\xi(r, z)$ is

their spatial two-point correlation, $d_A(z)$ is the usual angular size distance, and $H(z)$ is the Hubble ratio. It is clear that three factors contribute to the observed $w(\theta)$: the evolution of the galaxies themselves affects $N(z)$; the evolution of their clustering affects $\xi(r, z)$; and the background cosmological model affects H and d_A . Notice that $N(z)$ and $\xi(r, z)$ depend on the precise magnitude and colour criteria used to define the sample since galaxy abundances and clustering amplitudes depend sensitively on luminosity and colour. Notice also that intrinsically different galaxy populations will contribute to the integral at different redshifts.

Current data show a steady weakening of $w(\theta)$ as fainter and fainter samples are considered (Brainerd et al 1995; Villumsen et al 1996). For $R > 25$ significant correlations have so far only been detected for $\theta \leq 1$ arcmin. This corresponds to scales well below 1 Mpc and so is not really what is normally thought of as large-scale structure. Comparison with data at $z = 0$ requires consideration of the evolution of clustering in the strongly *nonlinear* regime. The current results could be substantially improved by constructing good deep photometric samples over large fields. A particularly interesting possibility would be the use of colour criteria to isolate high redshift subsamples. This should be possible with the newest wide-field imagers on big telescopes. Preliminary studies of the dependence of $w(\theta)$ on colour selection criteria already show a strong, and as yet poorly understood effect (Landy et al 1996).

4.2 Deep redshift surveys

Recent deep redshift surveys include the Canada-France Redshift Survey discussed in this volume by F. Hammer and O. LeFèvre, the Anglo-Australian B-limited surveys discussed here by R. Ellis and M. Colless, and the Hawaii deep survey (Cowie et al 1996). The CFRS, for example, contains redshifts for almost 600 galaxies and is about 85% complete to a magnitude of $I = 22.5$. Its median redshift is greater than 0.5. As samples get deeper it becomes *much* harder to analyse them in an analogous way to local surveys. This is not merely because it is more difficult to get redshifts for individual galaxies, but also because the sampling volume has a very large extent in the redshift direction ($\sim 10^3 h^{-1} \text{Mpc}$) so that many redshifts have to be obtained before there are enough galaxies within any given structure (of size 20 to 50 $h^{-1} \text{Mpc}$) for it to be mapped clearly. The situation is made worse by the expected weakening of large-scale structure with increasing redshift, and, at very high redshift, by the fact that only a few percent of faint galaxies are at $z > 2$.

As can be seen from O. LeFèvre's contribution, considerations of this kind led the VIRMOS project to conclude that they need redshifts for 10^5 objects. The use of colour criteria could provide a well defined sample of preselected high redshift objects to give this kind of project a better lever-arm for studying the evolution of clustering. In practice, studies of large-scale structure at high redshift are likely to be restricted, at least initially, to measuring two-point correlation functions for galaxies on scales of a few Mpc. The considerations of previous sections suggest that the major difficulty in interpreting the results will lie in

understanding the “bias” of the particular galaxy population observed. Indeed, this is already true for the CFRS where the major uncertainty in interpreting the measured correlations at $z = 0.5$ is in knowing which population of galaxies they should be compared with at $z = 0$ (LeFèvre et al 1996). It is unlikely that the problem of understanding the development of large-scale structure can be decoupled from that of understanding galaxy evolution.

Other approaches to structure at high redshift could involve samples of galaxy clusters or of quasars. Selecting clusters from optical data is much more complex than, say, measuring a correlation function, and it is particularly hard at high redshift because of the large number of foreground and background galaxies. Multiband colours (“photometric redshifts”) can undoubtedly play a major role in enhancing the apparent contrast of clusters, and distant cluster selected by X-ray luminosity or Sunyaev-Zel’dovich decrement may eventually be available. Critical points when analysing such samples will be the influence of the observational selection criteria and the relation of the distant objects to nearer clusters. For quasars, of course, similar considerations apply. In both cases the samples are sparse and so the clustering signal is difficult to measure.

4.3 Large-scale structure in absorption

There are a number of major advantages to using quasar absorption lines to probe large-scale structure: the probability of detecting any particular absorber depends only weakly on its position along the line-of-sight; absorbing systems are abundant along each line-of-sight; usable lines-of-sight are quite common – quasars with $B < 20$ have a typical separation of about 15 arcmin; the lines appear due to relatively unevolved material so that their relation to other components, for example the dark matter, may be relatively easy to understand; the absorbing gas is plausibly the raw material for galaxy formation and studies of its distribution and metallicity should therefore clarify how galaxies form. The best strategy for carrying out a substantial survey of large-scale structure at $z \sim 2$ to 2.5 is probably to use a multiband, wide-angle photometric sky survey to identify quasar candidates; intermediate resolution spectroscopy on a 4m-class telescope can then yield a confirmed quasar sample with a suitable redshift distribution; finally, high resolution multi-object spectroscopy on an 8m-class telescope would provide good absorber samples along each line-of-sight.

The Sloan and 2dF surveys will be able to carry out the first two of these functions, but they will not have the resolution or sensitivity to see the abundant, low column density absorbers along lines-of-sight to quasars with $B \sim 20$. As a result their ability to study clustering of the absorbers, although very useful, will be limited by the sparseness of their absorber sample. (For example, the comoving abundance of detected CIV systems will be comparable to the local comoving abundance of Abell clusters.) High resolution spectroscopy on a large telescope is critical to being able to measure structure reliably on the relatively small scales where it is expected to be significant at $z \sim 2$.

4.4 Large-scale structure from gravitational lensing

Gravitational lensing can be used in at least two different ways to detect large-scale clustering in the mass distribution. The first employs the fact that coherent gravitational shearing of the images of background galaxies induces polarisation, that is to say, images which are near each other on the sky have a weak tendency to line up. This effect can be detected by correlating the orientations of galaxies as a function of their angular separation using large, deep, and high quality photometric images taken during excellent seeing. This is a difficult measurement because the gravitationally induced excess ellipticities are of the order of one per cent. So far only upper limits (Brainerd et al 1995) or tentative detections (Villumsen 1996) of the effect have been published. With better cameras on large telescopes firm detections are quite feasible. The measured quantity, the polarisation correlation function, depends on the redshifts of the background galaxies, on the amplitude, shape and evolution of the power spectrum of mass fluctuations, and on the cosmic geometry (see Blandford et al 1991). For geometric reasons most of the effect is induced at $z \sim 0.5$.

A second effect of lensing is produced by its magnification and demagnification of background galaxies. This can result in an apparent clustering even if the background objects are, in fact, unclustered. The strength of the effect depends on whether the increased abundance of galaxies in magnified regions, caused by the lifting of faint systems above the sample magnitude limit, is outweighed by the increased separation, which magnification also produces (Broadhurst et al 1995). In practice the combined effect is quite weak and must be considered in combination with the intrinsic clustering of the faint galaxies. A first theoretical analysis is given by Villumsen et al (1996). Since image orientations are not used, there are no additional requirements on image quality beyond those normally needed to measure angular correlations to faint magnitude limits.

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Fig. 1. Slices through simulations of four cosmological models at $z = 0$.

Fig. 2. Slices through simulations of four cosmological models at $z = 1$.

Fig. 3. Slices through simulations of four cosmological models at $z = 3$.